Application of Fuzzy Logic to Safety Risk Assessment of China's Maritime Passages

Dao-Zheng Huang, Hao Hu, and Yi-Zhou Li

The maritime system has a high level of uncertainty, which makes it difficult to assess its safety. This paper proposes an improved formal safety assessment (FSA) method based on fuzzy logic and employing if–then rules, which model the qualitative aspects of human knowledge and reasoning processes. A fuzzy expert system is then designed to address FSA's risk assessment step. An investigation is performed to gain expert knowledge, which is essential to building this system. An example that assesses the safety of Chinese maritime passages is used to illustrate the methodology. The method is effective in the solution of problems with high uncertainty. Finally, suggestions are given to enhance the level of safety.

Maritime accidents, such as collisions, groundings, and oil spills, regularly destroy lives and property. For example, the April 2010 Deepwater Horizon oil spill in the Gulf of Mexico resulted in a reported \$3.12 billion in expenditures by British Petroleum, including the cost of the spill response, containment, relief well drilling, grants to the Gulf states, claims paid, and federal costs as of July 5, 2010. What is worse is that more than 400 species that live in the Gulf islands and marshlands are at risk, including several turtle species: the endangered Kemp's Ridley, the green, the loggerhead, the hawksbill, and the leatherback. In the national refuges most at risk, about 34,000 birds have been counted, including gulls, pelicans, roseate spoonbills, egrets, terns, and blue herons. After such an incident, maritime safety has attracted the attention of maritime authorities as well as researchers around the world.

In 2010, development of China's marine economy was formally included into the country's 12th 5-year plan. After rapid development for more than 30 years since implementation of the reform and the opening-up policy in 1978, China's economy now suffers from the bottleneck of energy and natural resources. To maintain sustainable development, the Chinese government has brought forward the marine economy policy, which provides further development of marine oil, navigation, and fishery resources.

Currently, China has an open economy highly dependent on the ocean. China obtains approximately 85% of its imported oil by sea, with around 40% to 45% coming from the Middle East and nearly a third from Africa (*1*). Chinese analysts and policymakers have had to face the reality that China will remain heavily dependent on maritime oil imports in the foreseeable future; these imports rely on the shipping lane that crosses, in turn, the Taiwan Strait, Malacca Strait, Indian Ocean, Hormuz Strait, and Persian Gulf, before finally reaching the Middle East. Therefore, how to guarantee the safety of the shipping lane is critically important for China.

A "maritime passage" is defined as a long narrow zone of water through which a large amount of vital goods transit. The difference between a shipping lane and a maritime passage is that a maritime passage refers to separate and strategic zones while a shipping lane is a continuous route from the place of departure to the destination. So the maritime passage is necessarily located in places connecting and spanning the worldwide economy centers and production bases, which also depend on the distribution of the world's productivity. The vital straits are the jaws of the marine passage system. For example, Malacca Strait is a typical maritime passage. The strait is the nearest shipping channel between the Indian Ocean and the Pacific Ocean, linking major Asian economies such as India, China, Japan, and South Korea. About 100,000 vessels pass through the strait annually, carrying about one-quarter of the world's traded goods, including Middle Eastern oil, Chinese manufactured goods, and Indonesian coffee. About a quarter of all oil carried by sea passes through the strait, mainly from Persian Gulf suppliers to Asian markets such as China, Japan, and South Korea.

To develop appropriate and effective security measures, it is necessary to carry out safety assessments. In safety engineering, the two most common fault modeling techniques are the failure mode and effects analysis and the fault tree analysis. These techniques are ways to find problems and make plans to cope with failures, as in probabilistic risk assessment.

It is difficult to assess the safety of systems with a high level of uncertainty because the input information is unclear and the decision criteria are vague. Accordingly, fuzzy logic is well-suited for dealing with such problems. It is also used to address uncertainty in a fault tree of a process safety analysis (*2*).

The objective considered in this paper is to assess—qualitatively and quantitatively—promote, and improve the marine safety of China's maritime passage. Safety of maritime passage is concerned with the natural environment, the economy, diplomacy, politics, and so on. This paper presents a fuzzy formal safety assessment (FFSA) method that introduces fuzzy logic into the extensively applied formal safety assessment (FSA).

LITERATURE REVIEW

FSA and Its Application

To promote and improve maritime safety, the International Maritime Organization (IMO) adopted FSA in 1993. It was initially

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advanced by the Maritime and Coast Guard Agency at the 62nd meeting of the Maritime Safety Committee, introducing FSA to the marine industry and putting it into use and asking its members to be actively involved in the research on ship safety (*3*).

FSA is a rational and systematic process for assessing maritime safety risks and evaluating the costs and benefits of IMO's options for reducing those risks (*4*). FSA provides a structural and systematic formal framework that can be used in a wide range of situations. It aims at supporting major decision making and can also be combined with other formal decision-making aids such as multiattribute utility analysis, the analytical hierarchy process, and decision trees, if a more detailed or quantitative analysis of the various decision alternatives is desired (*5*).

FSA within the IMO decision-making procedures comprises a five-step system covering the core risk analysis elements found in any industry or methodology (Figure 1). As the figure shows, three types of safety assessments are provided by FSA:

1. Three-step assessment, including hazard identification (Step 1), risk assessment (Step 2), and providing recommendations for decision making (Step 5);
2. Four-step assessment, including hazard identification (Step 1), risk assessment (Step 2), identification of risk control options (Step 3), and providing recommendations for decision making (Step 5); and
3. Five-step assessment, including hazard identification (Step 1), risk assessment (Step 2), identification of risk control options (Step 3), performance of a cost–benefit analysis (Step 4), and providing recommendations for decision making (Step 5).

After FSA was first advanced, many research projects combining FSA and other methods have been undertaken. Wang applied a subjective modeling tool in formal ship safety assessment (*6*). The model is an alternative in which nonnumerical safety data are supplied. Fuzzy logic–based relative risk assessment was introduced into FSA by Hu et al. (*7*). Georgios et al. used fuzzy logic for rating and ranking hazards (*8*).

Background on Fuzzy Logic

Fuzzy logic is a form of many-valued logic. It deals with reasoning that is approximate rather than fixed and exact. In contrast with traditional logic theory, where binary sets have two-valued logic (true or false), fuzzy logic variables may have a truth value that ranges in degree from 0 to 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions.

Fuzzy logic began with the 1965 proposal of fuzzy set theory by Zadeh (*9*). Although fuzzy logic has been widely applied to many fields, from control theory to artificial intelligence, it remains controversial among most statisticians, who prefer Bayesian logic, and some control engineers, who prefer traditional two-valued logic.

Fuzzy Sets and Membership Functions

A fuzzy membership function describes fuzzy sets that map from one given universe of discourse to a unit interval. This is conceptually and formally different from the fundamental concept of probability (*10*).

Fuzzy Inference System

The expert system uses feed-forward and -backward inference methods (*11*) that are used to identify which aspects of the conditional rules are fulfilled.

The following operators are used for fuzzy inference:

- Aggregation operator. This is used for fulfillments of the rules according to their initial conditions.
- Implication operator. The severities of fulfillments are computed at this level. The algebraic product and minimum operators are used for this purpose.

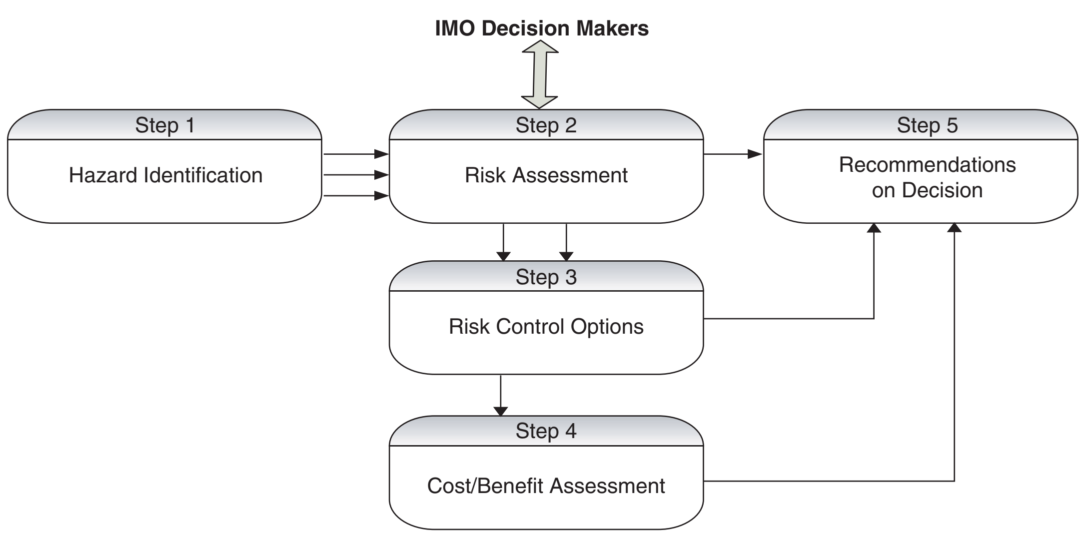

FIGURE 1 Formal safety assessment.

- Accumulation operator. This is used for accumulation of inferences among the fulfilled rules. The algebraic sum and maximum operators are used for this purpose.

Maritime Safety Assessment

Dobbins and Jenkins estimated coastal maritime risk by adapting a geographic information system–based highway planning traffic assignment model for use in maritime risk assessment (*12*). Eleye-Datubo et al. proposed a fuzzy Bayesian network (*13*), which incorporated the human element into a probabilistic risk-based model. Furthermore, fuzzy evidential reasoning is adopted in maritime security assessment (*14*).

METHODOLOGY

The first step of this research involves various knowledge acquisition techniques to generate a body of information that could be used in developing fuzzy linguistic variables and their associated membership functions. The procedure of the method is given as follows:

- Investigation and knowledge acquisition,
- Framework of fuzzy formal safety assessment,
- Hazard identification,
- Fuzzy expert system, and
- Recommendation of decision making.

Investigation and Knowledge Acquisition

In many practical situations, several approaches can be used to gather information and knowledge required to derive fuzzy rules. The knowledge acquisition process consists of a hybrid of knowledge acquisition methodologies, and the three most commonly used techniques are

1. Statistical data and information analysis,
2. Engineering practice, and
3. Domain expert experience.

These techniques are not mutually exclusive, and a combination of them is often the most effective way to create rules for the rule base. In this paper, an investigation into experts is performed to develop linguistic variables and rules. The investigation is discussed later in the case study.

Framework of FFSA

The aforementioned methods assume that the decision maker is able to provide exact assessments on the importance of evaluation criteria on the impact of alternatives. However, owing to the availability and subjectivity of information, it is extremely difficult to obtain exact assessment data about the fulfillment of the requirements of the criteria or the relative importance of each criterion. Classical decision-making methodologies are thus criticized for oversimplifying the decision-making process by forcing the experts to express their views on pure numeric scales. It is common sense that assessments made by experts are mostly subjective and qualitative (*15, 16*).

Fuzzy sets theory, originally proposed by Zadeh (*9*), is an effective means to deal with the vagueness of human judgment. This theory offers tools to handle linguistic terms by converting them to suitable fuzzy sets and numbers. Fuzzy multicriteria decision-analysis methods allow integration of linguistic assessments and weights in a multicriteria decision-analysis setting.

In the paper, fuzzy logic is used in FSA to assess the risk by linguistic valuables, which rarely give an exact value. And a fuzzy expert system is built to support decision making for the Chinese government.

Fuzzy logic in FSA is mainly used in the first step to describe the hazard by linguistic variables and in the second step to rank the risk. The application is illustrated in the case study section. Finally, if the result of the methodology is not satisfied, redefinition of FSA is recommended.

Hazard Identification

Hazard identification is the first and, in many ways, the most important step in risk assessment (*8*). An overlooked hazard is likely to lead to more error in the overall risk estimate than would an inaccurate consequence model or frequency estimate. The aim of hazard identification is to produce a comprehensive list of all foreseeable hazards to ensure no overlap. To distinguish between hazards and consequences, FSA defines a hazard as "a physical situation with potential for human injury, damage to property, damage to the environment or some combination" (*17*).

Various scientific safety assessment approaches can be applied in this step, such as preliminary hazards analysis, accident tree analysis, failure mode, effects and criticality analysis, and a hazard and operability study (*18*).

Fuzzy Expert System

A fuzzy expert system is a collection of membership functions, if–then rules, and logical operators that are used to establish a relationship between the input and the output variables. As shown in Figure 2, this system often consists of four components: fuzzy rule base, fuzzy inference engine, fuzzifier, and defuzzifier, which will be described to show how the fuzzy mathematical and logic principles are used in a fuzzy expert system. This paper assumes that $I = I_1 \times I_2 \times \cdots \times l_n \subset R^n$ is the input space and $O \subset R$ is the output space.

Fuzzy Rule Base A fuzzy rule base consists of a set of fuzzy if–then rules. It is the core of a fuzzy expert system. For example, the *l*th rule is of the following form:

$$\mathrm{Ru}^{(l)}\text{: If } x_1 \text{ is } A_1^l \text{ and/or} \ldots x_i \text{ is } A_i^l \text{ and/or} \ldots x_n \text{ is } A_n^l, \text{ then } y \text{ is } B^l \tag{1}$$

where $\mathrm{Ru}^{(l)}$ is the lth rule, A_i^l and B^l are fuzzy sets in $I_i \subset R$ and $O \subset R (i = 1, 2, \ldots, n)$, respectively, and $x = (x_1, x_i, \ldots, x_n)^T \in I$ and $y \in O$ are the input and output (crisp) variables of the fuzzy expert system (*19*). Let M be the number of fuzzy rules ($l = 1, 2, \ldots, M$ in Equation 1). To develop the rules for a fuzzy expert system, information can be obtained in two ways: (*a*) through expert knowledge and (*b*) through collected data. In this paper, an investigation into expert systems is performed to develop the rules.

Fuzzy Inference Engine The inference engine relates the consequences of the linguistic rule base with membership function

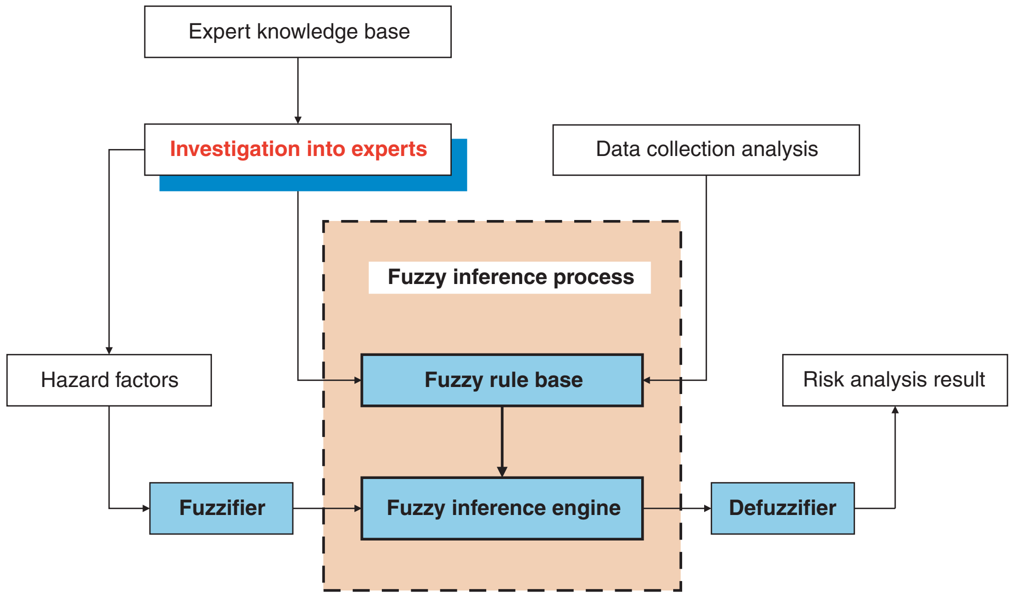

FIGURE 2 Overview of risk assessment through fuzzy expert system.

values to deduce the output for the corresponding input values. This model works on the commonly used Mamdani inference scheme. This process could be simply formulated as follows (*19–21*). Let A' be an arbitrary fuzzy set in I and the input to the fuzzy inference engine and B' be the output.

Given fuzzy set A' (which represents the precise x in A') and fuzzy relation $A \rightarrow B$ in $I \times O$ (which represents if x is A then y is B), a fuzzy set B' in O (which represents conclusion y is B') is referred to as (*19*)

$$\mu_{B'}(y) = \sup_{x \in I} t\left[\mu_{A'}(x), \mu_{A \rightarrow B}(x, y)\right] \tag{2}$$

where $\mu_{B'}(y)$ represents the membership value of y to fuzzy set B and sup represents the compositional rule of inference and is also called sup-star composition (*21*). If the rules are independent conditional statements, then M rules in the form of Equation 1 are interpreted as a single fuzzy relation Q_M in $I \times O$ defined by

$$Q_m = U_{l=1}^{M} \mathrm{Ru}^{(l)} \tag{3}$$

This combination is called the Mamdani combination. If the symbol "+" is used to represent S-norm, then Equation 3 can be rewritten as

$$(x, y) = \mu_{Ru^{(1)}}(x, y) + \cdots + \mu_{Ru^{(M)}}(x, y) \tag{4}$$

Then, by viewing Q_M as a single fuzzy if–then rule and using the generalized *modus ponens,* the output of the fuzzy inference is obtained as

$$\mu_{B'}(y) = \sup_{x \in I} t\left[\mu_{A'}(x), \mu_{Q_M}(x, y)\right] \tag{5}$$

If a minimum inference engine (*22*) is used,

$$\mu_{B'}(y) = \max_{l=1}^{M}\left[\sup_{x \in I} \min\left(\mu_{A'}(x), \mu_{A_1^l}(x_1), \ldots, \mu_{A_n^l}(x_n)\right), \mu_{B^l}(y)\right] \tag{6}$$

Given fuzzy set A' in I, the minimum inference engine gives the output set B' in O, according to Equation 6.

Fuzzifier Because, in most applications, the input and output of the fuzzy system are real-valued numbers, interfaces must be established between the fuzzy inference system and the environment. The "fuzzifier" is defined as a mapping from a crisp value point $x^* \in I$ to a fuzzy set A' in I.

Defuzzifier The "defuzzifier" is defined as a mapping from fuzzy set B' in $O \in R$ to crisp point $y^{\Delta} \in O$. Although there are a number of techniques for use of a defuzzifier, this paper uses the center average method. This defuzzifier method is commonly used (suppose two rules are applied):

$$y^{\Delta} = \frac{y^{-1} * w_1 + y^{-2} * w_2}{w_1 + w_2} \tag{7}$$

Conceptually, the crisp output would be computed as the center average of the final output set (*21*).

CASE STUDY

Main Maritime Passages for China

Figure 3 shows the main shipping lanes in the world. China has seven main shipping lanes, as follows.

The first lane is between China and European countries, starting from the Chinese coast and crossing in turn the South China Sea, the Strait of Malacca, the Indian Ocean, the Suez Canal, the Mediterranean Sea, and finally the North and Baltic Seas. This lane is China's most important one, handling 30% of China's total foreign trade and around 85% of China's oil imports, despite being the most unstable because of rampant piracy and complicated political relationships.

The second lane is from the eastern Pacific of China to North America's Caribbean coast, which passes through the Hawaiian

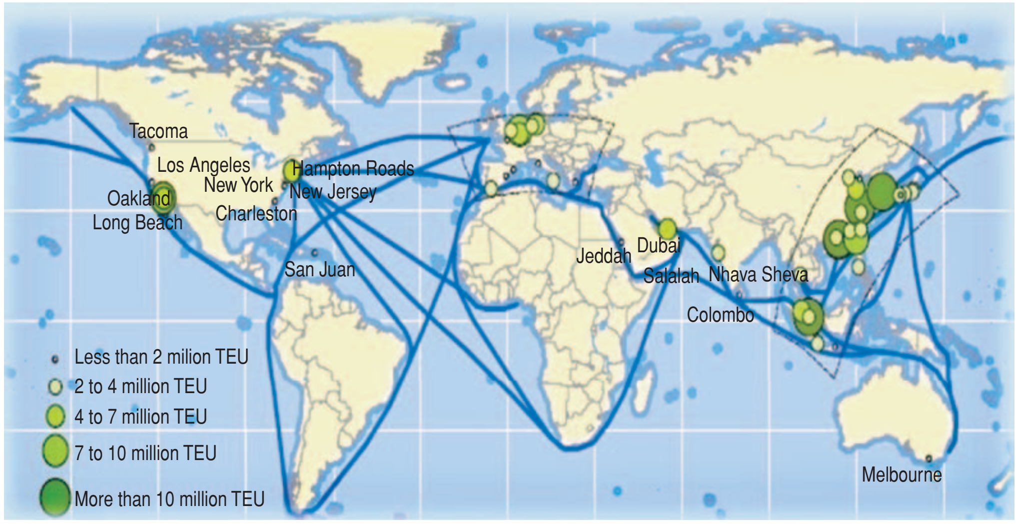

FIGURE 3 Shipping lanes in world.

Islands and the Panama Canal. This lane handles 10% of China's total foreign trade.

The third lane sets out from the northern Chinese coast and passes the Sulfur Islands, Wake Island, and the Line Islands before crossing the equator into the South Pacific and reaching South America's western ports. This lane carries oil, iron ore, and other strategic resources to China. With the economic and trading relationship between China and South America becoming increasingly close, this lane plays an increasingly important role in maritime transport. The fourth lane travels from China's southeast coast to Southeast Asia and Australia, bearing 18% of China's foreign trade. This lane carries oil, gas, timber, iron ore, manganese ore, and uranium ore, among other goods and resources.

The fifth lane is the North Pacific shipping lane, stretching from the coast ports of China to the West Coast of Canada, the United States, and Mexico. Ships pass both southward through the Osumi Strait and the East China Sea or northward through the Sea of Japan and the Tsushima Strait. Alternative routes include the Strait of Chongjin, the Soya Strait, and the Okhotsk Sea to the North Pacific. This lane bears 13% of China's foreign trade. The sixth lane is from China's coast to South Korea and Japan, which takes 15% of China's total transport task of foreign trade. The last lane starts from West, Eastern, and Southern Africa and crosses the Cape of Good Hope, the Indian Ocean, the Malacca Strait, and the South China Sea before reaching China's coast. This lane handles 30% of China's oil imports and a significant portion of iron ore, manganese ore, and various nonferrous metal imports.

These shipping lanes possess some important passages. Table 1 shows some typical maritime passages, their importance to China, and related hazards.

Safety Assessment of China's Maritime Passages

Suitable data necessary for some steps of the FSA process is very difficult to get. When data are not available, expert judgment, physical laws, simulations, and analytical models may be used to achieve useful results. In this paper, expert judgment is adopted and an investigation into the safety of China's maritime passage is performed.

According to the investigation, three main factors that influence China's maritime safety most are piracy (P), diplomatic and economic relationships with other countries (DE), and military (M). The escalation of piracy and armed terrorism, such as piracy in Somalia, against ships has seriously endangered life at sea and affected international trade and economic development. Peace and development are the theme of the current world. Friendly diplomatic relationships with countries along strategic passages would provide great convenience. The military has the effect of deterrence and is the last choice to protect safety. Countries that have a strong military, especially a navy, can control critical passages when war breaks out, so as to cut off an enemy's marine supply.

Risk Assessment with Fuzzy Expert System

In this section, a fuzzy expert system is designed to assess the risk of hazards. The three hazards are regarded as inputs to the system. The output is risk level.

DE describes the diplomatic and economic relationship with other countries. To estimate DE, one may use such linguistic variables as bad, average, good, and excellent. Figure 4*a* shows the P (piracy) fuzzy sets (few, average, many) definition. In a similar way, Figure 4*b* shows the DE fuzzy sets (few, average, good, excellent) definition

TABLE 1 Maritime Passages for China and Their Hazards

Maritime Passage	Importance to China	Hazard
Strait of Malacca	Critical to economic development and energy security	Piracy, haze, wreck
Strait of Taiwan	Taiwan is a part of China	Political issue
Strait of Hormuz	Chokepoint of oil transportation	Piracy, unstable politics in the Middle East
South China Sea	Transportation passage, marine resources	China's territorial disputes over Sprat Island, piracy

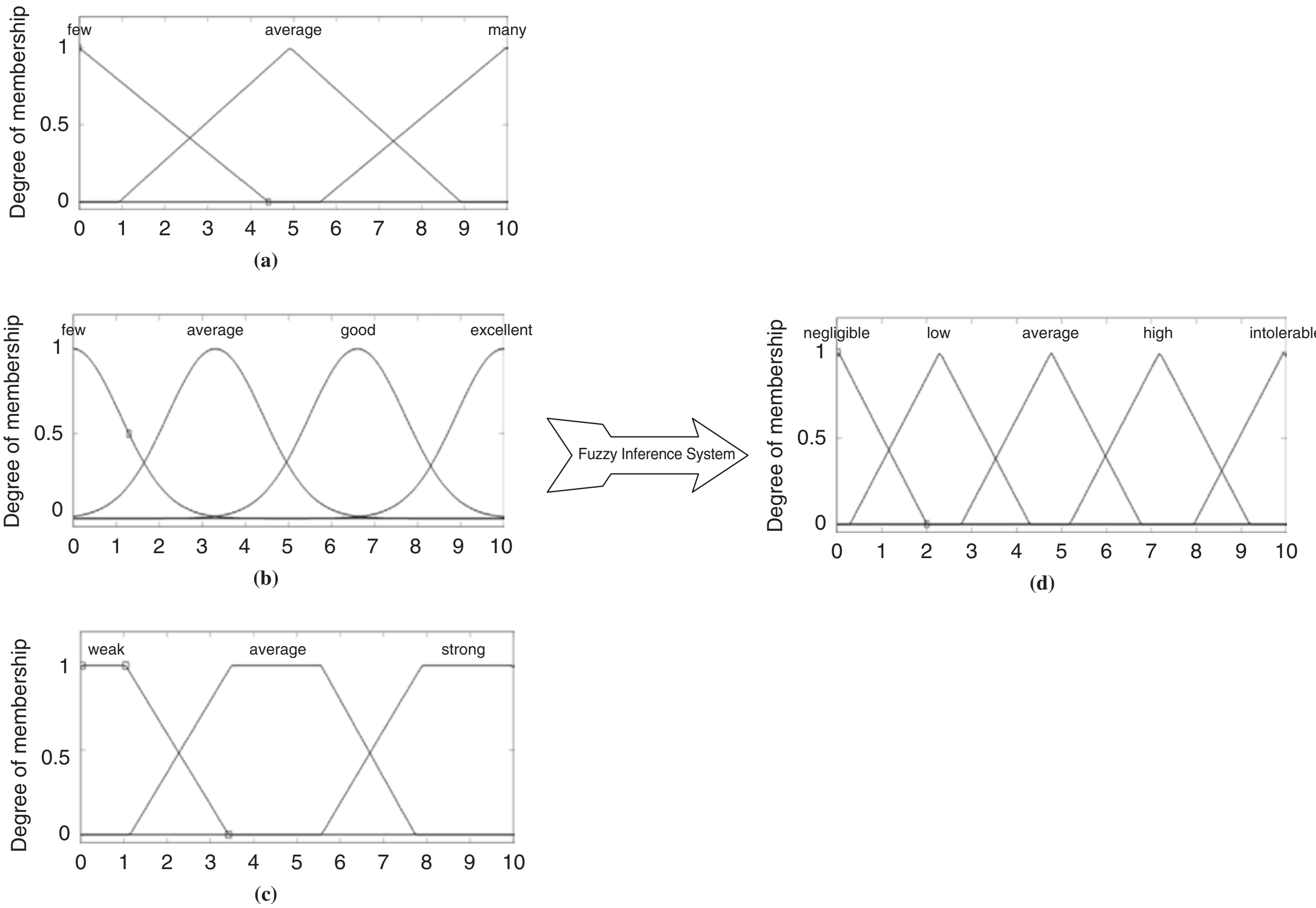

FIGURE 4 Membership functions of inputs and outputs: (*a*) piracy, (*b*) diplomatic and economic relationship, and (*c*) military, and (*d*) risk level from fuzzy inference system.

and Figure 4*c* shows the M (military) fuzzy sets (weak, average, strong) definition. How to explain the fuzzy sets is very important. With piracy as an example, then, according to Table 2, when the number of piracies is less than 250 per year, it is a few; when the number of piracies is between 250 and 350 per year, it is average; when the number of piracies exceeds 350 per year, it is many.

The simplest membership functions are formed by straight lines. Of these, the simplest two are triangular membership and trapezoidal membership, which are commonly used to describe risks in safety assessment (*23*).

In safety assessment, it is common to express risk level (RL) by degrees to which it belongs to such linguistic variables as intolerable (no safety), high (poor safety), average (average safety), low (good safety), and negligible (absolute safety), which are referred to as RL expressions. The output set can be defined by using fuzzy RL expression sets in the same way as the fuzzy inputs. Figure 4*d* shows the fuzzy RL expression sets.

In accordance with knowledge acquisition and investigation, 34 rules used in this study are listed in Table 3.

As for Chinese maritime safety, piracy is given a score of 4.8. China believes in the use of diplomacy rather than the use of military power. The value of diplomatic and economic relationships with other countries is 5.2. China is one of the countries that have nuclear weapons but no aircraft carriers, the most important weapon for a

TABLE 2 Variables for Piracy

	Year										
Variable	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Crisp value of piracy	252	210	309	471	370	383	452	330	266	241	282
Linguistic variable	Average	Few	Average	Many	Many	Many	Many	Average	Average	Average	Average

TABLE 3 Rules of System

Rule	Piracy	Diplomatic and Economic Relationship	Military	Risk Level
1	If few	And bad	And weak	Then intolerable
2	If few	And bad	And average	Then high
3	If few	And bad	And strong	Then average
4	If few	And average	And weak	Then high
5	If few	And average	And average	Then average
6	If few	And average	And strong	Then low
7	If few	And excellent	And weak	Then low
8	If few	And excellent	And average	Then negligible
9	If few	And excellent	And strong	Then negligible
10	If few	And good	And weak	Then average
11	If few	And good	And average	Then low
12	If few	And good	And strong	Then negligible
13	If average	And bad	And weak	Then intolerable
14	If average	And bad	And average	Then high
15	If average	And bad	And strong	Then average
16	If average	And average	And weak	Then high
17	If average	And average	And average	Then average
18	If average	And good	And strong	Then low
19	If average	And good	And weak	Then average
20	If average	And excellent	And weak	Then average
21	If average	And excellent	And average	Then low
22	If average	And excellent	And strong	Then negligible
23	If many	And bad	And weak	Then intolerable
24	If many	And bad	And average	Then intolerable
25	If many	And bad	And strong	Then high
26	If many	And average	And weak	Then intolerable
27	If many	And average	And average	Then high
28	If many	And average	And strong	Then average
29	If many	And excellent	And weak	Then high
30	If many	And excellent	And average	Then average
31	If many	And excellent	And strong	Then negligible
32	If many	And good	And weak	Then intolerable
33	If many	And good	And average	Then high
34	If many	And good	And strong	Then average

navy. And China has no military base in strategic straits or canals. So four points are given to the value of China's military.

The detailed calculation process follows:

Step 1. Fuzzify. In this evaluation procedure, only two rules are applied:

- Rule 17. If P is average, DE is average, and M is average, then the RL is average.
- Rule 18. If P is average, DE is average, and M is good, then the RL is low.

The fuzzification process is described as follows:

- For Rule 17, P at 4.8 corresponds to $\mu_P = 0.9$ for the average membership function; DE at 5.2 corresponds to $\mu_{DE} = 0.33$ for the average membership function; D at 4 corresponds to $\mu_D = 1$ for the average membership function.
- For Rule 18, P at 4.8 corresponds to $\mu_P = 0.9$ for the average membership function; DE at 5.2 corresponds to $\mu_{DE} = 0.4$ for the average membership function; M at 4 corresponds to $\mu_M = 1$ for the good membership function.
- In this manner, each input variable is fuzzified over all the qualifying membership functions required by rules.

Step 2. Apply fuzzy operator. The antecedents of the two rules are evaluated. For example, in the application of Rule 17, the fuzzy membership values ($\mu_{P,17}$, $\mu_{DE,17}$, $\mu_{M,17}$) = (0.9, 0.33, 1), respectively. The fuzzy AND operator ($\mu_r = \mu_{P,17}, \mu_{DE,17}, \mu_{M,17}$) simply selects the minimum of the three values, 0.33. The application of the fuzzy operator generated the results as shown below for each rule involved in the evaluation process.

Step 3. Apply implication method. Implication is implemented for each rule. The following expression is used to generate the membership value of the consequent RL estimates for the rth rule: $\mu(H_n; n = 1, 2, 3, 4, 5)_r = \mu_r$, where $\{H_1, H_2, H_3, H_4, H_5\}$ represents fuzzy sets of RL {negligible, low, average, high, intolerable}.

- For Rule 17, $\mu(H_3; \text{average})_{17} = \mu_{17} = 0.33$.
- For Rule 18, $\mu(H_2; \text{low})_{18} = \mu_{18} = 0.4$.

Step 4. Defuzzify. In accordance with Equation 12, crisp output is obtained:

$$y^{\Delta}_{RL} = \frac{0.33 * 4.5 + 0.4 * 2.3}{0.33 + 0.4} = 3.3$$

It is between the risk levels average and low.

Discussion of Fuzzy Process

China's maritime safety is between the low and average levels. China should cooperate with other countries. Figure 5 illustrates the correspondence between inputs and outputs. Assume that piracy is 5 points. Figure 5*a* shows the relationship between risk level and diplomatic and economic relationship; Figure 5*b* shows the relationship between risk level and the military. Finally, a three-dimensional graph illustrates the integrated relationship between risk and those two factors. The graph indicates that risk level decreases as the diplomatic and economic relationship with other countries improves or the military becomes stronger.

CONCLUSIONS

This paper presented an improved formal safety assessment method based on fuzzy logic. The method is effective in solving problems with high uncertainty. Some conclusions and recommendations are summarized below:

- Fuzzy logic is extremely useful in analyzing systems with a high level of uncertainty. A fuzzy expert system is first used in FSA's risk assessment step. When exact data are difficult to obtain, the fuzzy expert system designed with expert knowledge is a reasonable alternative.
- Many safety assessment methodologies are simply frameworks to assess safety. Therefore, the details of a given methodology should be considered carefully to ensure that the techniques are appropriate and will provide the desired insights.
- The safety of China's maritime passages is not guaranteed. According to the assessment result, the risk level is between average and low. There is room to improve safety. It is recommended that China should cooperate with other countries to ensure safety of its maritime passages.

This paper is the first step toward a safety analysis of China's maritime passage and a demonstration of fuzzy logic's potential in

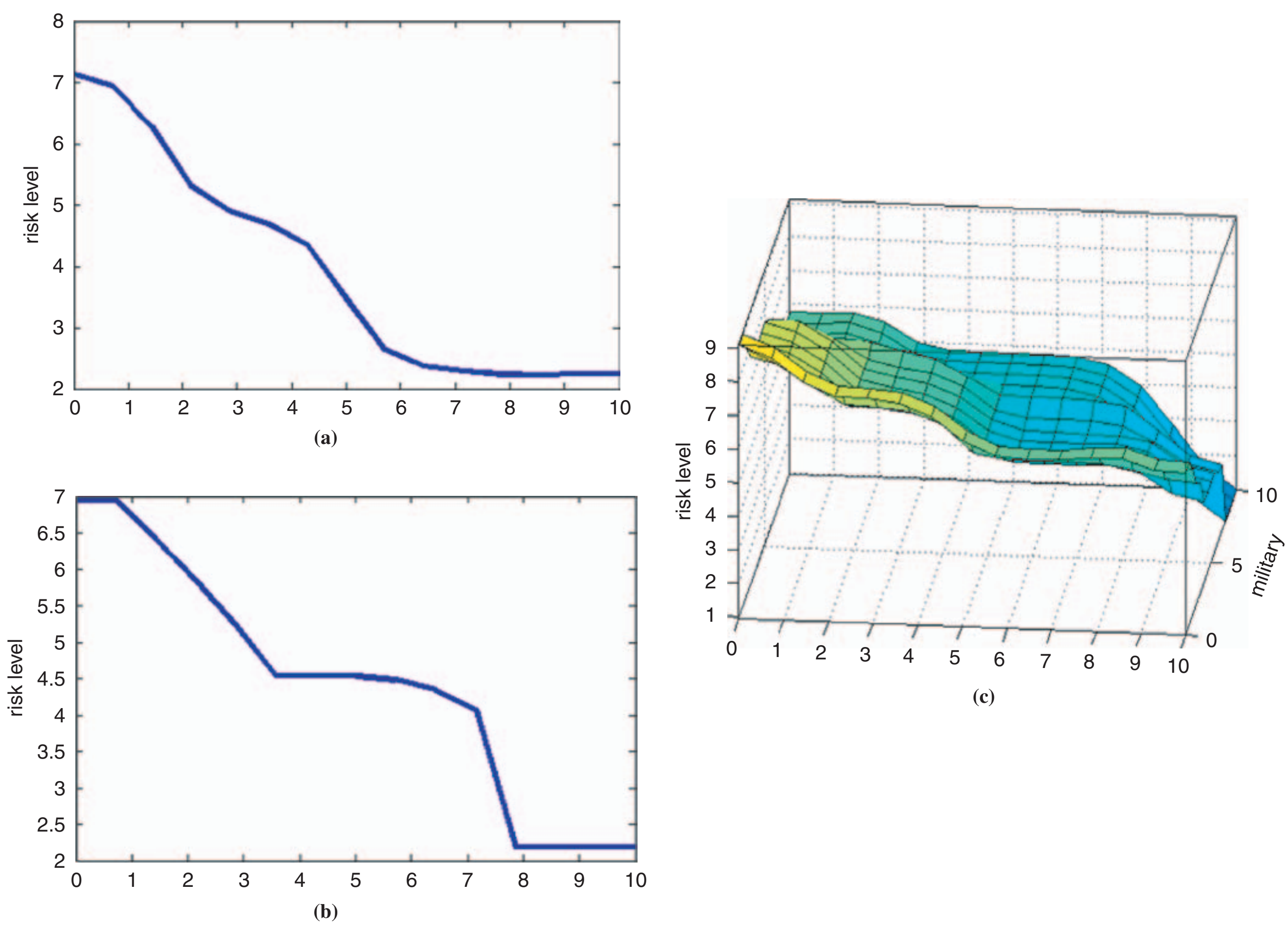

FIGURE 5 Correspondence between inputs and outputs: (*a*) risk level and diplomatic and economic relationship, (*b*) risk level and military, and (*c*) risk level and both diplomatic and economic relationship and military in three-dimensional graph.

the field of safety assessment. However, lack of reliable safety data has been the most difficult problem in safety assessment of various engineering activities. To improve the reliability and efficiency of the method, further studies are necessary. In particular, a database would be particularly helpful for the establishment of a high-quality model and valid membership functions and rules. Such work would make safety assessment more complete, more accurate, and more accessible to researchers, industry, and government planners.

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